AFRL-RX-WP-TP-2010-4053

FATIGUE VARIABILITY IN THROUGH-TRANSUS PROCESSED Ti-6Al-2Sn-4Zr-6Mo (PREPRINT)

Alisha L. Hutson and William J. Porter

University of Dayton Research Institute

James M. Larsen

Metals Branch
Metals, Ceramics & NDE Division

JANUARY 2010

Approved for public release; distribution unlimited.
See additional restrictions described on inside pages

STINFO COPY

AIR FORCE RESEARCH LABORATORY
MATERIALS AND MANUFACTURING DIRECTORATE
WRIGHT-PATTERSON AIR FORCE BASE, OH 45433-7750
AIR FORCE MATERIEL COMMAND
UNITED STATES AIR FORCE

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YY)*: January 2010

2. REPORT TYPE: Journal Article Preprint

3. DATES COVERED *(From - To)*: 01 January 2010 – 31 January 2010

4. TITLE AND SUBTITLE: FATIGUE VARIABILITY IN THROUGH-TRANSUS PROCESSED Ti-6Al-2Sn-4Zr-6Mo (PREPRINT)

5a. CONTRACT NUMBER: FA8650-04-C-5200

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER: 62102F

6. AUTHOR(S)

Alisha L. Hutson and William J. Porter (University of Dayton Research Institute)
James M. Larsen (AFRL/RXLM)

5d. PROJECT NUMBER: 4347

5e. TASK NUMBER: RG

5f. WORK UNIT NUMBER: M02R3000

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Metals Branch (AFRL/RXLM)
Metals, Ceramics & NDE Division
Materials and Manufacturing Directorate
Wright-Patterson Air Force Base, OH 45433-7750
Air Force Materiel Command, United States Air Force

University of Dayton Research Institute
Dayton, OH 45431

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Air Force Research Laboratory
Materials and Manufacturing Directorate
Wright-Patterson Air Force Base, OH 45433-7750
Air Force Materiel Command
United States Air Force

10. SPONSORING/MONITORING AGENCY ACRONYM(S): AFRL/RXLMN

11. SPONSORING/MONITORING AGENCY REPORT NUMBER(S): AFRL-RX-WP-TP-2010-4053

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES

Journal article submitted to *Scripta Materialia*. PAO Case Number: 88ABW-2009-4816; Clearance Date: 18 Nov 2009. The U.S. Government is joint author of this work and has the right to use, modify, reproduce, release, perform, display, or disclose the work. Paper contains color.

14. ABSTRACT

Variability in fatigue behavior of a through-transus forged titanium alloy was examined. Through-transus forging develops a microstructure balanced for strength, fatigue resistance and fracture toughness. Low cycle fatigue specimens extracted from a heat-treated forging were tested at a single stress at 260°C; resulting fatigue lives and variability were characterized as a function of local microstructure. A crack growth life computation was performed, assuming immediate initiation of a microstructure-scale crack. The result corresponded reasonably with an estimated minimum fatigue life.

15. SUBJECT TERMS

through-transus forging, Titanium alloys, fatigue, modeling, texture

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT:	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON (Monitor)
Unclassified	Unclassified	Unclassified	SAR	12	Reji John

19b. TELEPHONE NUMBER *(Include Area Code)*: N/A

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39-18

Fatigue Variability in Through-transus Processed Ti-6Al-2Sn-4Zr-6Mo

Alisha L. Hutson*, William J. Porter, and James M. Larsen

Abstract

Variability in fatigue behavior of a through-transus forged titanium alloy was examined. Through-transus forging develops a microstructure balanced for strength, fatigue resistance and fracture toughness. Low cycle fatigue specimens extracted from a heat-treated forging were tested at a single stress at 260°C; resulting fatigue lives and variability were characterized as a function of local microstructure. A crack growth life computation was performed, assuming immediate initiation of a microstructure-scale crack. The result corresponded reasonably with an estimated minimum fatigue life.

Keywords

Through-transus forging; Titanium alloys; fatigue, modeling, texture

Variability in the fatigue behavior of titanium alloys is a well-known, but often poorly understood, phenomenon. A number of efforts have been made to characterize the sources of such fatigue variability, with varying success, depending on the specific alloy and microstructure [1-5]. Through-transus processed microstructures in alloys such as Ti-6Al-4V and Ti-6Al-2Sn-4Zr-6Mo have proven to be among the most difficult to characterize because microstructural variations that occur within individual forgings mask the impact of initiation mechanisms, and the narrow processing window required to obtain the desired microstructure may lead to variations between material batches [6].

This investigation focused on two main objectives: characterizing the variability in fatigue behavior within a single forging and evaluating the life-limiting behavior. A series of carefully repeated experiments was conducted under a single stress and temperature condition, with representative material sampling from across the forging cross-section, to provide meaningful insight into the mechanisms that control variability in fatigue behavior. Corresponding fatigue crack growth life estimates were computed using this data to help interpret the experimental results.

The material used in this investigation was from a through-transus processed Ti-6Al-2Sn-4Zr-6Mo forging. Continuous processing on cooling through the β-to-α-phase boundary is designed to produce a fully transformed microstructure that is generally free of continuous regions of primary alpha phase [6-10]. Since slight variations in cooling rate affect the completeness in eliminating the primary alpha, some microstructural variations are expected [7]. Inspection of cross-sections of the material used in the current work indicated some mild microstructural texture variation (consistent with normally processed material), so specimens from the forging were grouped according to three locations, denoted as locations A, B & C (shown in Figure 1). Experimental results from these regions were compared to determine if the observed texture correlated with variations in fatigue behavior.

The geometry used in this study was a smooth-bar with a round gage section 12.7 mm long by 4 mm in diameter and a transition to the grip 13.1 mm long with a 32.5 mm transition radius. All specimens were machined with their load axis aligned in the circumferential orientation with respect to the forging (Figure 1), and the specimen surfaces were low-stress ground and polished to a surface finish of RMS8. The elastic modulus, Poisson's ratio, and yield strength of the material were identified as 115 GPa, 0.33 and 1120 MPa, respectively [11].

Fatigue tests were conducted at 260°C under constant amplitude loading at 30 cycles per minute using a stress ratio, R, of 0.05. A total of 32 fatigue tests were performed at an applied maximum stress of 827 MPa: 8 specimens from region A, 7 from region B, and 17 from region C. Crack initiation sites were located on each fractured specimen, and the results were

identified as either "surface" or "internal" initiations. Fatigue lives were compared according to forging location and crack initiation location.

A power law regression of crack growth data for this material was used as a basis to calculate the crack propagation lives for the temperature and R conditions of the experiments, over a range of applied stresses. A power law model with coefficients "C" and "m" set to 1.62e-11 MPa√m and 3.04, respectively, was employed to obtain the estimates. The fracture toughness was estimated at 53 MPa√m, and the power law was extended below the long-crack threshold value so that propagation lives incorporating an estimate of small + long crack growth behavior could be obtained, similar to fatigue life calculations in the literature for Titanium alloys [5,12]. A semi-elliptical surface crack with a depth, a_i, of 10 μm was assumed as the initial crack size, with applied stresses ranging from 750 to 950 MPa, to generate an estimate of the lower bound of an S-N curve for fatigue life comprised entirely of crack growth.

The fatigue test results for this study are shown on the S-N chart in Figure 2. Data shown in this plot are divided based on the forging locations from Figure 1, with slightly different plotted stresses used to aid data visibility. The fatigue life data ranged from ~95,000 to >1.5 million cycles. Region C data clearly dominate the higher fatigue life values, while Region B represents the lowest fatigue lives, indicating some effect of the region from which the specimen was extracted on fatigue behavior. Material from region C (away from the forging center line) experienced more flow during the forging process than material from regions A and B (close to the forging center line), as evidenced by tightly aligned flow lines revealed on the polished and etched forging cross section. Micro-hardness testing of various locations throughout the forging cross section also suggests that region C specimens have higher apparent relative strength properties characteristic of a more refined microstructure produced by faster cooling rates in thinner sections as compared to thicker ones. The subtle differences in the microstructural texture of these regions most likely play a role in the higher fatigue life values associated with material from region C.

Fatigue data such as these may be analyzed statistically to project a B.1 fatigue life, which is the fatigue life corresponding to a probability of failure of <0.1% (or <1 in 1,000), and is calculated assuming a log-normal distribution of fatigue lives. The data from this study are shown in Figure 3 on a log(cycles) vs. probability of failure (PoF) plot, both as a single population (small crosses) and divided based on the three previously defined forging locations. Statistics for each population are also included. A regression analysis of the data, when treated as a single population (solid black line), provides an estimate of the B.1 fatigue life for the data of N_f ~ 50K cycles. The same data, treated as three separate populations, indicate an estimated B.1 life (shown with dashed lines indicating the statistical regression) of ~60K cycles for Region A/B and ~90K cycles for Region C (A – circles, B – diamonds, C – triangles). Note that the data for Regions A and B do not appear to be distinct populations, so a single line was used to represent both of these data sets. Thus, this comparison of the single- and multiple-population analyses indicates that treating the data as separate populations will result in higher predicted B.1 lives than if the data were treated as a single population.

The data for Regions A/B and C were also segregated based on where cracks in the samples initiated, either on the surface or internally. Information on the location of the initiation sites was obtained by inspecting each sample's fracture surface in the scanning electron microscope (SEM). Results are shown in Figure 3 where hollow symbols represent specimens in which cracks initiated at the surface, and solid symbols represent specimens in which cracks initiated internally. The lowest fatigue lives correspond to surface initiations for all three material regions; the highest fatigue lives were all internal initiations. However, if the extremes are excluded, no other trend may be discerned, particularly if data from Regions A and B are considered together, as the previous statistical analysis suggests. Additionally, SEM characterization of these initiation sites did not reveal any pronounced differences in mechanisms for internal versus surface initiations. Also noteworthy is the absence of smooth,

faceted initiation sites usually associated with grain boundary alpha present in β-processed material. Representative fracture surface photos of both initiation types are shown in Figure 4.

Estimates of fatigue crack growth lives for a range of applied stress are shown on the S-N chart in Figure 2. At the stress level where the experiments were performed, the predicted fatigue crack growth life from the microstructural scale to failure was ~37K cycles. As might be expected, all of the fatigue life data reported here are higher than the predicted crack growth life, with apparent initiation lives ranging from 60% to over 95% of the total fatigue lifetime. However, the variability in fatigue life is quite large, and the true minimum life limiting fatigue behavior has almost certainly not been captured in the 32 tests conducted in this study.

If the life limiting behavior is assumed to be approximated by the B.1 fatigue life, then the 37K cycle fatigue life predicted by the crack growth analysis for the 827 MPa stress condition is quite reasonable. Nominal power law-based crack growth properties were assumed for these estimates, with the power law fit extended below the long-crack threshold to serve as a first approximation to the small crack correction [12]. A number of factors that influence computations of crack growth were not taken into account, including variability in the long crack growth data, effect of microstructure on the initial crack size, a rigorous treatment of small crack behavior, and the effect of surface residual stresses produced by the specimen machining process. Despite these exclusions, the crack growth prediction is approximately 75% of the B.1 fatigue life of 50K cycles, with all of the data taken as a single population, and is approximately 50% of the B.1 fatigue life of 60K cycles for the A/B data population. Assuming that the difference between the crack propagation life approximation (37K cycles) and the B0.1 fatigue lives (50K to 60K cycles) shown in Figure 3 can be used to approximate the proportion of life spent in crack initiation, then the results indicate initiation lives in the range of 25% to 40%, depending on forging location, for the life limiting behavior.

In summary, the wide variability in fatigue lifetime behavior suggested by preliminary data from literature was observed in the current fatigue results. Some of the variability was attributed to microstructural texture within the forging. Despite this difference in fatigue lives with forging location, no indication of the mechanisms responsible could be identified from inspection of the crack initiation sites, and no trend was observed based on whether initiations occurred internally or on the surface of the specimen. An estimate of life-limiting fatigue behavior was calculated assuming a zero initiation life, and using a power law fit to long-crack growth rate data obtained from the same material source. The estimated life compared well with B.1 fatigue lives obtained from a statistical analysis of the data, assuming a normal data distribution and indicating that a fracture based fatigue life system is plausible. An area of continuing promise for understanding these phenomena is probabilistic meso-scale modeling.

This work was performed at the Air Force Research Laboratory, Materials and Manufacturing Directorate, Wright-Patterson Air Force Base, OH 45433-7817 under on-site contract number FA8650-04-C-5200. The authors gratefully acknowledge the support of Dr. Leo Christodoulou of the Defense Advanced Research Projects Agency (DARPA) under DARPA order S271 and Dr. David Stargel and Dr. Victor Giurgiutiu of the Air Force Office of Scientific Research (AFOSR) under task 2306-6M2AL8.

References

[1] A.K. Polasik, S.K. Jha, M.J. Mills, J.M. Larsen, H.L. Fraser, “The Role of Microstructure on Fatigue Life Variability in Alpha/Beta Processed Ti-6Al-4V,” Materials Damage Prognosis, J.M. Larsen, L. Christodolou, J.R. Calcaterra, M.L. Dent, M.M Derriso, W.J. Hardman, J.W. Jones and S.M. Russ, Eds., TMS, Warrendale, PA, 2005 , pp. 121-128.

[2] S.K. Jha, et.al., Scripta Materialia, 48 (2003), pp. 1637-1642.

[3] S.K. Jha, J.M. Larsen, A.H. Rosenberger, G.A. Hartman, in Probabilistic Aspects of Life Prediction, ASTM STP 1450, W.S. Johnson and B.M. Hillberry, Eds., ASTM International, West Conshohocken, PA, 2003.
[4] S.K. Jha, K.S. Ravichandran, Scripta Materialia, 48 (2003), pp. 1207-1212.
[5] S.K. Jha, J.M. Larsen, A.H. Rosenberger, Acta Materialia (2005), pp.1293-1304.
[6] J.C. Williams, Journal of Materials Processing Technology, 117 (2001), pp. 370-373.
[7] G. Lütjering and J.C. Williams, “Titanium,” Springer-Verlag (2007), pp 292-294.
[8] S.L. Semiatin, Metalworking: Bulk Forming, vol. 14A, ASM Handbook, ASM International (2005) pp. 3-10.
[9] C. Sauer, G. Luetjering, Mat. Sci. & Engrg., A319-321 (2001), pp. 393-397.
[10] C. Sauer, G. Luetjering, J. of Mater. Processing Tech., 117 (2001), pp. 311-317.
[11] MatWeb, Your Source for Materials Information,” MatWeb Material Property Data. (1996-2007) Automation Creations, Inc., www.matweb.com, search on “Ti-6Al-2Sn-4Zr-6Mo STA”
[12] S.K. Jha, J.M. Larsen, A.H. Rosenberger, Engineering Fracture Mechanics, 76 (2009), pp. 681-694.

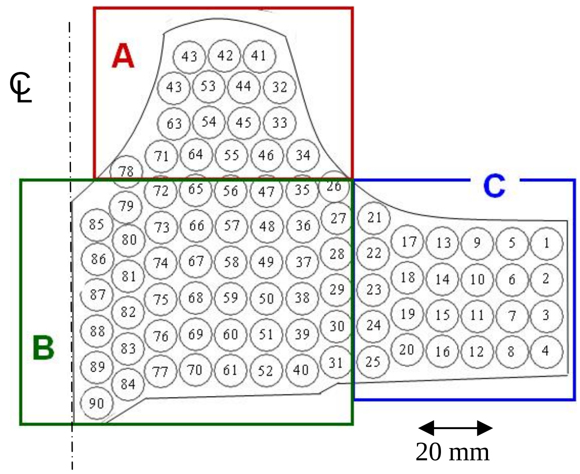

Figure 1. Specimen extraction layout of material forging cross-section.

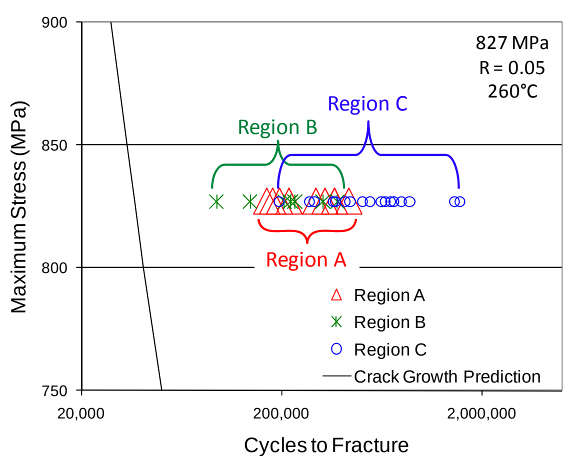

Figure 2. S-N fatigue test results with fatigue crack growth life computation curve.

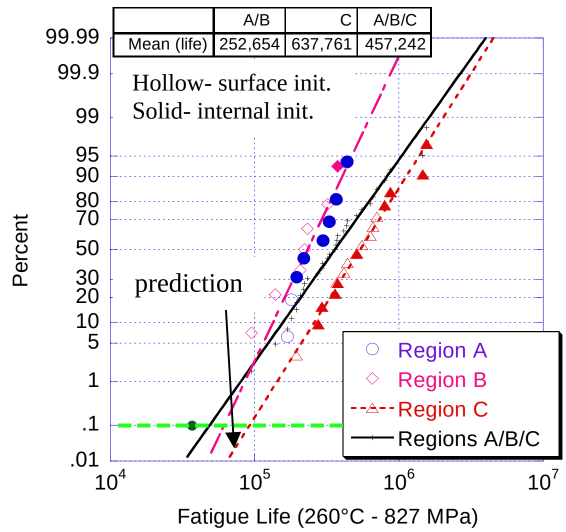

Figure 3. Probability of failure vs. log(cycles) all forging locations, shown with the predicted crack growth life estimate for the experimental test condition.

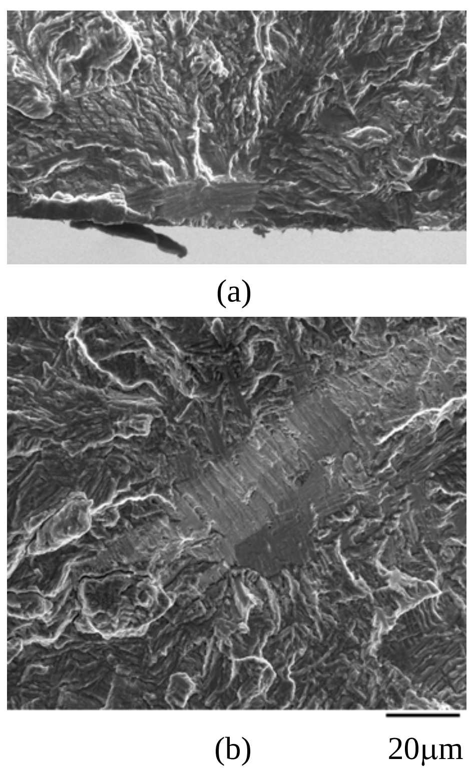

Figure 4. Typical observed fracture surfaces from surface (a) and internal (b) fatigue crack initiations.